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After the Higgs: status and prospects of the electroweak fit of the Standard Model and beyond

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We present an update of the global Standard Model (SM) fit to electroweak precision data under the assumption that the new particle discovered at the LHC is the SM Higgs boson. In this scenario all parameters entering the calculations of electroweak precision observables are known, allowing to over-constrain the SM at the electroweak scale and to assert its validity. Within the SM the W boson mass and the effective weak mixing angle can now be accurately predicted from the global fit. Their results exceed in precision the direct measurements. A determination of the S, T and U parameters, which parametrize the oblique vacuum corrections, is given. We examine the impact of the STU observables on a model of modified couplings of the Higgs boson to gauge bosons, and compare this with the corresponding analysis of LHC measurements of the signal strength of Higgs channels. Future measurements at the International Linear Collider (ILC) promise to improve significantly the experimental precision of key observables used in the fit. We conclude with an outlook to the global electroweak fit for the ILC with GigaZ option.

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1. Introduction

Assuming the newly discovered scalar boson to be the Higgs boson of the Standard Model (SM), then the insertion of its measured mass, m_H, of around 126 GeV, into the global electroweak fit of the SM overconstrains the electroweak sector. It allows to predict key observables with a precision exceeding that of their direct measurements [1]. These observables become sensitive probes of new physics [2].

By exploiting contributions from radiative corrections, the global electroweak fit can also be used to determine the couplings of the Higgs boson to gauge bosons, through the formalism of S, T, U parameters. In this note these coupling constraints are compared and combined with LHC measurements of the signal strength in various Higgs channels.

The projected experimental uncertainties from the International Linear Collider (ILC) with GigaZ option [3] are used to derive the expected precision of SM predictions for electroweak observables[1]. Furthermore the future prospects of the electroweak fit are studied for constraining the aforementioned Higgs couplings.

2. Key predictions of the SM fit

A detailed description of the calculations and experimental input used in the electroweak fit is given elsewhere [1]. The inclusion of M_H in the fit results in a large improvement in precision for the indirect determination of several key SM parameters. In particular, an improvement in precision of more than a factor of two is observed for the indirect determination of M_W and $\sin^2\theta^{\ell}_{\rm eff}$.

The prediction for M_W obtained from the fit is

$$\begin{aligned} M_W &= (80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo})\ {\rm GeV}\,, \\ &= (80.359 \pm 0.011_{\rm tot})\ {\rm GeV}\,, \end{aligned} \tag{2.1}$$

which exceeds the experimental world average in precision. The different uncertainty contributions originate from the uncertainties in the input values of the fit. The dominant uncertainty is due to the top quark mass, followed by the theory uncertainty of 4 MeV. The deviation between the value of M_W obtained from the fit and the current direct measurement is not significant (1.2σ).

The indirect determination of $\sin^2\theta^{\ell}_{\rm eff}$ gives

$$\begin{aligned} \sin^2\theta^{\ell}_{\rm eff} &= 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{\rm theo}\,, \\ &= 0.23150 \pm 0.00010_{\rm tot}\,, \end{aligned} \tag{2.2}$$

which is compatible and more precise than the average of the LEP/SLD measurements. The total uncertainty is dominated by that from the measurements of $\Delta\alpha_{\rm had}$ and m_t.

[1] GigaZ: the operation of the ILC at lower energies like the Z pole or the WW threshold allows the experiments to perform precision measurements of the electroweak sector of the SM. At the Z pole the physics at LEP1 and SLC can be revisited with the data collected during a few days. Several billion Z boson decays can be studied within 1–2 months [3].

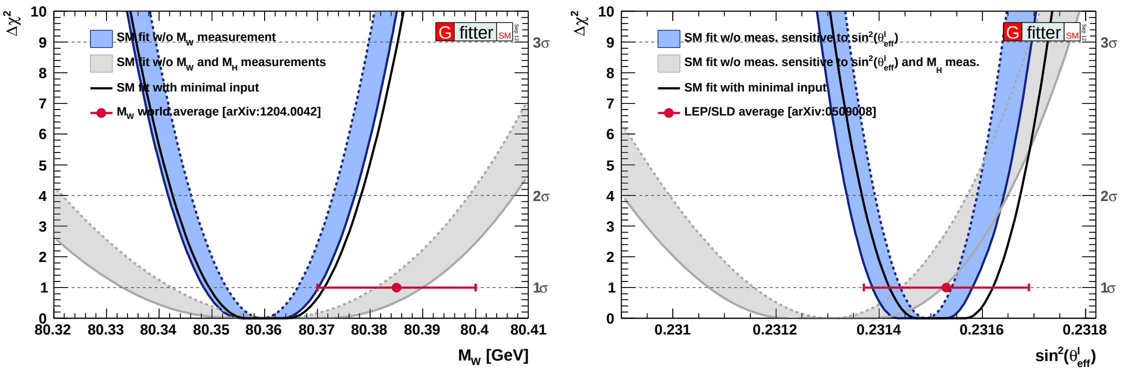

Figure 1: $\Delta\chi^2$ profiles for the indirect determination of M_W (left) and $\sin^2\theta^\ell_{\rm eff}$ (right). The result from a fit including (without) M_H as input parameter is shown in blue (grey). The dotted lines indicate the fit result by setting the theoretical uncertainties to zero and the band corresponds to the full result. Also shown are the direct measurements and the SM prediction using a minimal set of parameters (black solid lines) [1].

The $\Delta\chi^2$ profiles versus M_W and $\sin^2\theta^\ell_{\rm eff}$ without using the corresponding measurements are shown in Fig. 1. Solid blue lines show the result of the fit including M_H, where the effect of the theory uncertainty is shown as blue bands. The same fit, without information on M_H is shown in grey. Also shown are the direct measurements of the aforementioned W mass and the LEP/SLD average of $\sin^2\theta^\ell_{\rm eff}$, which show good agreement with the predicted values.

3. Higgs couplings from oblique parameters

If the scale of new physics (NP) is much higher than the mass of the W and Z bosons, beyond the SM physics appears dominantly in the calculation of the electroweak precision observables (EWPO) through vacuum polarization corrections, also known as oblique corrections. Their effects on the electroweak precision observables can be parametrized by three gauge self-energy parameters (S,T,U) introduced by Peskin and Takeuchi [4]. Constraints on the S,T,U parameters are derived elsewhere [1]. We find: $S = 0.03\pm0.10$, $T = 0.05\pm0.12$ and $U = 0.03\pm0.10$, with correlation coefficients of $+0.89$ between S and T, and -0.54 (-0.83) between S and U (T and U). The STU parameters are found to be small and consistent with zero.

Precision measurements of the properties of the new Higgs-like boson are of critical importance. Among its key properties are the couplings to the each SM fermion and boson, which are predicted to depend linearly on the fermion mass and quadratically on the boson mass.

Modified Higgs couplings have been probed by ATLAS and CMS in various benchmark models [5]. These employ an effective theory approach, where higher-order modifiers to a phenomenological Lagrangian are matched at tree-level to the SM Higgs boson couplings [6]. In a popular model all boson and all fermion couplings are modified in the same way, scaled by the constants κ_V and κ_F, respectively[2]. This benchmark model uses the explicit assumption that no (other) new

[2]Equivalent notations are: $\kappa_V \equiv c_V \equiv a$, and $\kappa_F \equiv c_F \equiv c$.

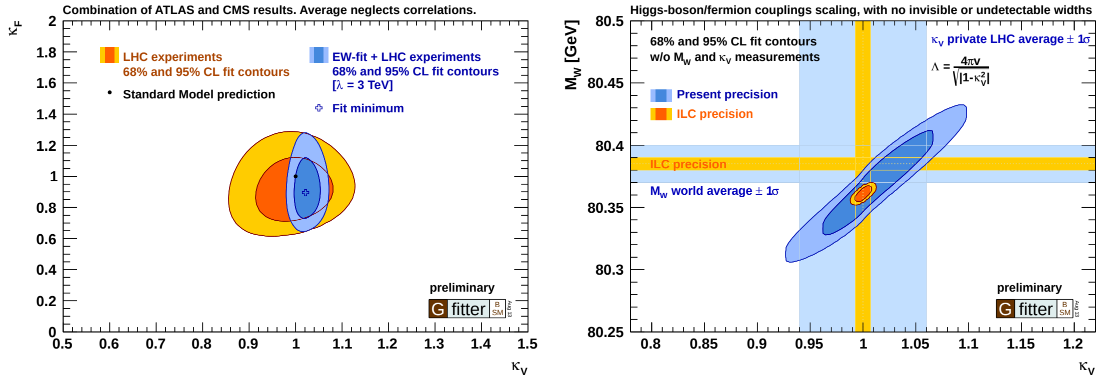

Figure 2: Left: Measurement of κ_F versus κ_V at 68 % and 95 % CL from a combination of present ATLAS and CMS results (orange), overlaid with the constraint of κ_F versus κ_V when including the EW-fit (blue). Right: Comparison of the direct M_W and κ_V measurements and their indirect predictions for $\lambda = 3$ TeV, for present (blue) and ILC/GigaZ (yellow/orange) precision, at 68 % and 95 % CL.

physics is present. The combined analysis of electroweak precision data and Higgs signal-strength measurements has been studied by multiple groups [7, 8].

The main effect of this model on the EWPO is from the modified Higgs coupling to gauge bosons. The corrections to the Z and W boson propagators can be expressed in terms of STU [7],

$$S = \frac{1}{12\pi}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right),\; T = -\frac{3}{16\pi\cos^2\theta_{\rm eff}^{\ell}}(1-\kappa_V^2)\log\left(\frac{\Lambda^2}{M_H^2}\right),\; \Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}} \tag{3.1}$$

with $U = 0$. The cut-off scale Λ represents the mass scale of the new states that unitarise longitudinal gauge-boson scattering. Most BSM models with additional Higgs bosons giving positive corrections to the W mass predict values of κ_V smaller than 1. Here the nominator λ is varied between 1 and 10 TeV, and is nominally fixed to 3 TeV ($4\pi v$).

Shown in Fig. 2 (left) are κ_V and κ_F as obtained from a combination of ATLAS and CMS results using all publicly available information on the measured Higgs signal strength modifiers μ_i. Correlations between the individual measurements of μ_i are neglected as these are not supplied by the experimental collaborations. However, we find that individual results by ATLAS and CMS for κ_V are well reproduced by this procedure. The measured value of κ_V from this combination gives 1.00 ± 0.06. Also shown in this plot is the combined constraint on κ_V (and κ_F) from the LHC experiments and the electroweak fit.

The electroweak fit results in $\kappa_V = 1.032^{+0.036}_{-0.025}$, $1.024^{+0.024}_{-0.018}$, and $1.019^{+0.019}_{-0.014}$, for cut-off parameters $\lambda = 1$ TeV, 3 TeV and 10 TeV, respectively. Including constraints from electroweak precision observables, the constraint on κ_V can be improved by a factor of more than three. There is a mild dependency on the chosen value for λ, but all values result in small but positive deviations from unity. For $\kappa_V \sim 1.02$ and $\lambda = 4\pi v$, the new physics scale $\Lambda \gtrsim 15$ TeV.

The positive deviation of κ_V from 1 is driven by the small discrepancy between the observed and predicted values of the W mass, as shown in Fig. 2 (right). To determine the predicted ellipses, the measured value of M_W and the current measurements of μ_i have been removed from the EW fit.

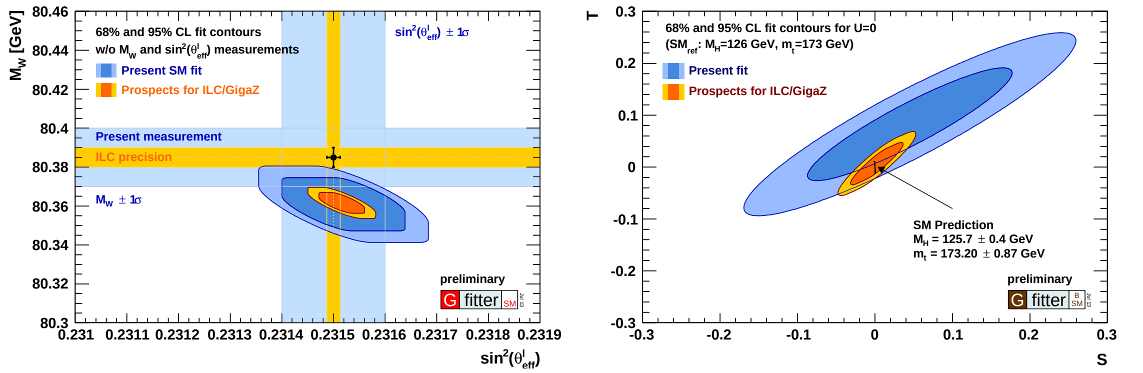

Figure 3: Left: ILC projection of the contour lines of 68%, 95% CL allowed regions in the M_W–$\sin^2\theta^\ell_{\rm eff}$ plane. Shown are the current indirect determinations (blue) and the expected precision using prospects for ILC measurements (orange). The present (prospects) direct measurements are shown as light blue (orange) bands. Right: contour lines of 68%, 95% CL allowed regions on the S and T parameters for $U = 0$. The ILC prediction is shown in orange.

4. Prospects of the electroweak fit at the ILC/GigaZ

A future e^+e^- collider would allow, among others, for precise measurements of the EWPO and to further assert the validity of the SM through the electroweak fit. In the following we study the impact of expected EWPO measurements on the SM electroweak fit assuming the predicted precisions obtained for the International Linear Collider (ILC) with the GigaZ option. The central values of the input observables have been chosen to agree with the SM prediction for a Higgs mass of 126 GeV according to the present measurement.

For the ILC/GigaZ the following assumptions are made [3]. For M_W a precision of 5 MeV obtained from cross section measurements at and above the WW production threshold is assumed. Scans of the $t\bar{t}$ production threshold are expected to yield an experimental precision on the top quark mass of approximately 30 MeV. The conversion of the measured m_t into $\overline{\rm MS}$ using perturbative QCD adds an estimated uncertainty of 100 MeV, which dominates the total uncertainty. Measurements of the weak left-right asymmetry $A_{\rm LR}$ from hadronic Z decays are expected to translate into a precision for $\sin^2\theta^\ell_{\rm eff}$ of $1.3 \cdot 10^{-5}$. Finally, the uncertainty of the partial decay width of the Z boson can be improved to yield a $4 \cdot 10^{-3}$ precision in R^0_ℓ (from currently $25 \cdot 10^{-3}$). An improvement of M_H beyond the LHC accuracy does not lead to improvements in the EW fit.

For this future scenario we also assume that the determination of $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ can be improved from currently $10 \cdot 10^{-5}$ to $4.7 \cdot 10^{-5}$ [9].

Significant progress will also be required for the SM predictions to match the experimental precision. At present, the most important theoretical uncertainties in the fit are those affecting the predictions of M_W and $\sin^2\theta^\ell_{\rm eff}$, at $\delta_{\rm th} M_W = 4$ MeV and $\delta_{\rm th}\sin^2\theta^\ell_{\rm eff} = 4.7 \cdot 10^{-5}$ [10]. For the future scenarios, we assume that these uncertainties reduce to 1 MeV and 10^{-5}, respectively.

Prospects for the precision of the simultaneous indirect determination of $\sin^2\theta^\ell_{\rm eff}$ and M_W are shown in Fig. 3 (left) together with the present and expected precision of the $\sin^2\theta^\ell_{\rm eff}$ and M_W measurements. The gain in precision of the indirect measurements is about a factor of three with respect to the current determinations. Assuming that the central values of $\sin^2\theta^\ell_{\rm eff}$ and M_W do not change from their present values, a deviation between the SM prediction and the direct measurements would be prominently visible.

The precisely measured EWPO would also help to constrain new physics through oblique corrections. The expected constraints on the S and T parameters are shown in Fig. 3 (right), where an improvement of more than a factor of 3 seems to be possible. Fig. 2 (right) also shows the prospects for predicting and measuring κ_V versus m_W at the ILC/GigaZ. At the ILC, the predicted uncertainties on the measurements of the Higgs to W and Z gauge boson coupling constants are both 1% [11]. The predicted uncertainty of κ_V varies between 0.005 and 0.010 for the ILC scenario, depending on the value of λ.

5. Conclusion

We have reported here on the most recent results from the electroweak fit [1]. The knowledge of the Higgs mass dramatically improves the SM predictions of, in particular, M_W and $\sin^2\theta^\ell_{\rm eff}$, and sets a benchmark for corresponding new direct measurements.

We have also carried out an analysis of the Higgs coupling data in a popular benchmark model. Here the inclusion of electroweak precision observables yields constraints on the bosonic coupling κ_V three times stronger than using Higgs coupling data alone.

Finally, the perspectives of the electroweak fit considering the ILC running also at energies at the Z-pole have been analyzed. Assuming a good control over systematic effects, the predictions for the M_W, $\sin^2\theta^\ell_{\rm eff}$, STU and κ_V are improved with a factor of three or greater.

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